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Cardinal Effect on Seasat Images of Urban Areas

The orientation of residential street patterns was found to have a significant and predictable effect on the radar image.

Abstract: *Several investigators have noticed a somewhat unexpected tendency for large sections of an urban area to radically change tone on different orbital radar images and simulations. This paper attempts to examine the problem quantitatively using Seasat Synthetic Aperture Radar data. A very significant impact from cardinal effect is indicated. In addition, much of it seems to be predictable.*

Introduction

The strength of a radar echo is dependent upon the interaction of many complex influences. Most important among these are the electrical and geometric properties of the target object. Detailed information is available in the literature (Long, 1975; Moore, 1976). Of the geometric properties, one of the most potentially significant is the so-called "cardinal effect," noted over 20 years ago by Levine (1960). In general, this is the tendency of a radar to produce very strong echos from a city street pattern or other linear feature oriented perpendicular to the radar beam. The buildings directly *along* the radar beam will also yield strong radar returns. Because the streets in many parts of the country are located in accordance with the Township and Range land subdivision system, they often run north-south and east-west, producing strong radar reflections from flights in any of these four cardinal directions. Thus, the term cardinal effect was born, although it is used more broadly today, to describe these enhanced echoes, whether the features happen to be north-oriented or not.

Since the time of Levine's early work it has been repeatedly demonstrated that cardinal effect is primarily the result of dihedral reflection from buildings and other structures oriented with the streets (Bryan, 1979; Graham, 1976). This has come to be known as "corner reflector effect." However, it has been considered very much of a special case, having little interest for the majority of radar image users. In Figure 1 the reader can see the classic illustration of this. On the left is an aircraft radar image of Sun City, Arizona with its three circular road patterns. On the right is a Seasat image brought up to the same scale. Despite the extreme enlargement, the cardinal effect is quite obvious here also.

Recently there has been considerable new interest in civilian applications of side-looking radar, especially for urban areas. Reasons for this include declassification of higher resolution sensors and moving target indicator imagery, the successful although brief operation of the Seasat radar, and the arrival of an operational Space Shuttle radar in the 1980's. For example, in preparation for the Shuttle radar mission, the Jet Propulsion Laboratory conducted a number of radar flights across the Los Angeles area, attempting to simulate the orbital radar. In reporting on these experiments, Bryan (1979) found that large sections of the city seemed to drop out almost completely or else produce highly enhanced radar

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Photogrammetric Engineering and Remote Sensing,
Vol. 48, No. 3, March 1982, pp. 399-404.
0099-1112/82/4803-0399$02.25/0

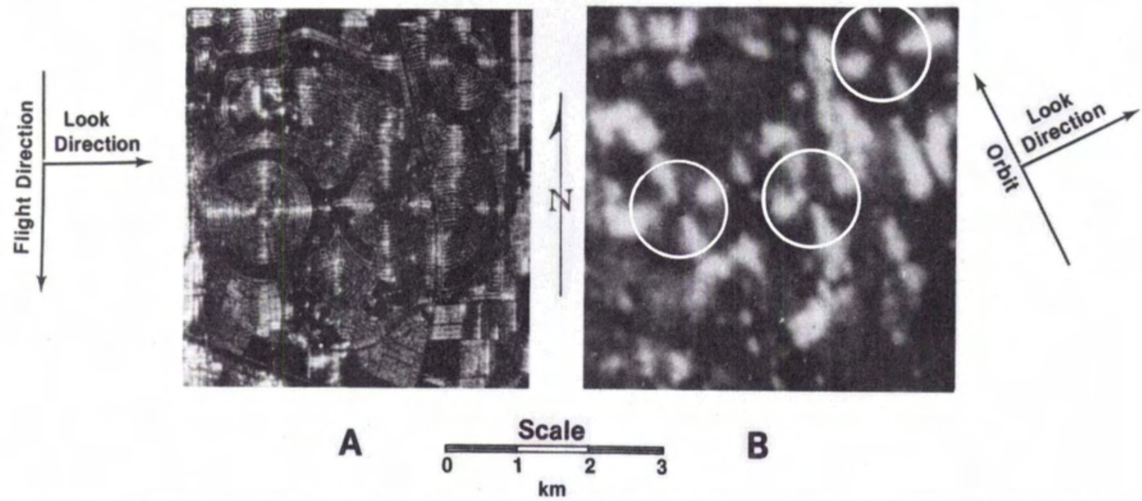

FIG. 1. Synthetic aperture radar, L-Band HH, imagery of Sun City, Arizona. (A) Aircraft data collected by and courtesy of Environmental Research Institute of Michigan (Bryan, 1979). (B) Seasat-1 digital data processed by Jet Propulsion Laboratory and courtesy of NOAA.

echoes on the imagery. The existing literature on cardinal effect led one to expect a few highly accentuated streets—not an entire section of the city to radically change its tone. Bryan was able to tie this phenomena to street orientation in relation to the radar beam; thus, essentially, the cardinal effect.

DATA COLLECTION

From his aircraft radar data, Bryan was able to establish a relationship between strength of the radar echo and orientation of the street pattern within Los Angeles (Bryan, 1979). Most aircraft radar systems look primarily outward, nearly at grazing angles for distant objects. In contrast, Seasat operates much closer to the vertical. Therefore, one might expect minimal cardinal effect from the orbital images.

These problems have also been investigated by Henderson and Anunta (1980) using existing imagery from a variety of radar sensors. Briefly, they were attempting to measure the detectability of small urban places on radar images. They found that settlement detectability was significantly influenced by radar azimuth on aircraft imagery in which the settlement was oriented parallel to the flight line. For other orientations, their results were mixed. However, on the Seasat imagery, an obvious and consistent relationship emerged. Waite and his colleagues (Waite *et al.*, 1980) briefly mention the obvious impact of cardinal effect on Seasat imagery of urban areas in Lafayette, Louisiana. They then go on to establish, in some detail, the very apparent relationship between row orientation for agricultural fields and strength of the radar backscatter.

The present authors have attempted to go one step further by concentrating on satellite radar data and by diversifying the urban landscape somewhat more. The goal here has been to corroborate earlier work primarily from aircraft data and to quantify more conclusively the strength of the cardinal effect for major urban areas.

Radar data for the Seasat experiments were available for four major urban areas, each with considerable diversity of street orientations. Included in the study were 140 test neighborhoods selected from Seasat L-band Synethtic Aperture Radar images of Baltimore, Boston, Harrisburg (Pennsylvania), and El Paso. Seasat has a 24 cm-wavelength Synethetic Aperture Radar (SAR) which is HH polarized and has a 25-metre resolution. In each case, the test neighborhoods were selected using the U.S. Geological Survey 7½ minute Quadrangle maps and existing aerial photography. Primarily residential sections of the city were sought out, each having right angle streets and a high degree of internal consistency regarding street directions. Another part of the selection criteria was to obtain as many differently oriented street patterns as possible. For Baltimore, El Paso, and Harrisburg, both ascending and descending orbital passes were available. This meant that their 91 test sites could each be examined from two different radar look directions, creating a total data set of 231 observations. These aspects of the data set are summarized in Table 1.

Once the test sites were selected, their street orientations were measured from the topographic map according to the method of Bryan (1979). That is, an angle *phi* was determined for each site as the angle between the actual radar azimuth at that

TABLE 1. GEOGRAPHICAL AND ORBITAL CHARACTERISTICS OF THE DATA SET. THE LARGE NUMERALS IN EACH CASE REPRESENT THE NUMBER OF TEST POINTS (i.e., neighborhoods) USED FROM EACH IMAGE.

ORBIT:	CITY: Baltimore	El Paso	Harrisburg	Boston	All
Ascending	46 Rev 1296	19 Rev 853	26 Rev 1296	—	91
Descending	46 Rev 558	19 Rev 559	26 Rev 759	49 Rev 1232	140
All	92	38	52	49	231

latitude and the street orientation.* Here radar azimuth means the *look direction* of the radar antenna. This is out to the side of the spacecraft, perpendicular to the flight line. It should be noted that there is a slight variation in orbital heading of the satellite, depending upon the latitude of the test site. For example, the spacecraft bearing is about 24° for Baltimore, Boston, and Harrisburg, but drops to 22° for the lower latitude of El Paso. The specific streets were selected in such a way that phi is always an acute angle of 45° or less. This concept is illustrated geometrically in Figure 2. Thus, a phi of zero would imply that the radar was looking straight down one of the two sets of perpendicular streets.

The distribution of possible street orientations is shown in Figure 3. As can be seen, most possible phi angles are included in the sample. Ideally, for the present work, each class would have an equal frequency.

The data set was completed by simply measuring the image tone of each of the test sites on the appropriate Seasat image. This was done using a 1 millimetre aperture densitometer directly on the Seasat positive images. For each of the 231 test sites, three readings were taken and averaged. To help compensate for any differences in photographic processing, the fog level for each image was subtracted from the readings. Obviously, digitally correlated Seasat negatives would have been better for these measurements, but unfortunately they were not available at the time.

DATA ANALYSIS

A review of the existing literature leads one to several unanswered questions. First, is there a reliable relationship between street orientation and radar response for urban areas? If so, is the image tone of an urban area predictable on that basis? Finally, as the value of phi increases from zero, is there a threshold value at which the radar reflection curve flattens out?

In an effort to answer these questions from the present data, several statistical techniques were utilized. An intuitive impression of the relationships involved can be gained from a glance at Figure 4. This is a scatter plot of the dependent variable, image tone, against phi and is directly comparable with a similar plot from aircraft data

* Bryan actually used the notation "theta" for this angle. Due to the common use of theta in the literature to refer to incidence angle, it was deemed best to avoid that notation here.

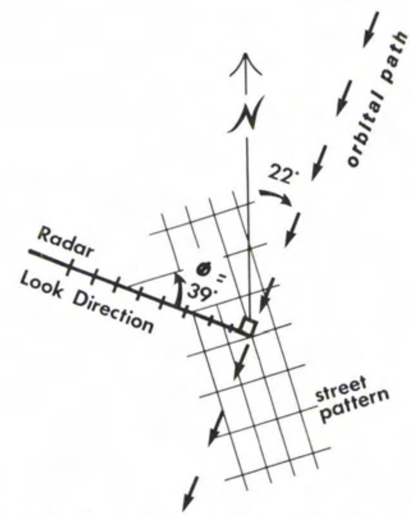

FIG. 2. Diagram illustrating the method of defining street orientation in relation to the radar look direction; this angle is defined as phi. Note that the orbital bearing of 22 degrees illustrated above actually varies slightly according to the latitude of the target area (see text).

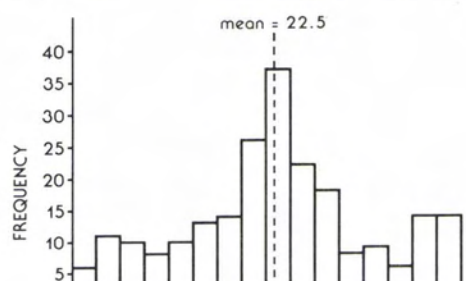

FIG. 3. Frequency distribution of street orientations (i.e., phi) for the entire data set of 231 urban sites.

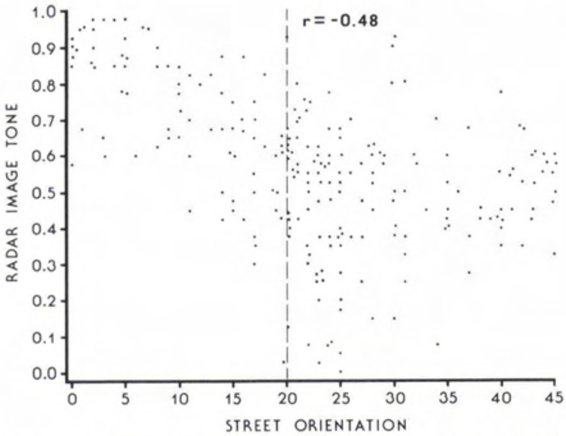

FIG. 4. Scatter diagram of grey value against street orientation angle, phi, for all 231 observations.

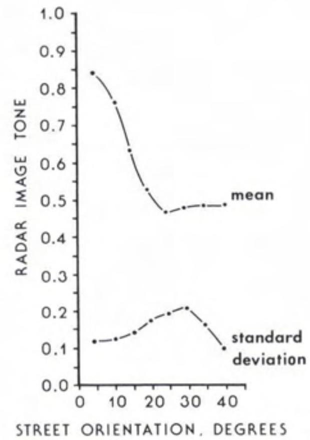

FIG. 5. Generalized plot of image tone against street orientation (phi).

included in Bryan's 1979 paper. From this plot it is immediately apparent that there is a moderately strong relationship between grey value and phi. Clearly, higher values of image tone (i.e., strength of the radar echo) are associated with lower values of phi.

A more objective expression of the strength of this relationship is provided by the correlation coefficient, r. Here, r takes on a value of -0.48 and is statistically significant at the 95 percent Confidence Level. This is a clear indication that there is a bona fide inverse relationship between grey value and street orientation. The square of the correlation coefficient, known as the coefficient of determination or r^2, is commonly used to indicate the proportion of the total variation in Y which is explained by a change in X alone, ignoring all other influences. In our study an r^2 of 0.23 suggests that about one-fourth of the total variation in image tone for urban areas on these images can be attributed to street orientation alone. Among all the complex influences on the radar echo, it is quite striking that this one factor should account for such a large proportion of the variation.

In Figure 4 the scatter of the points is obviously very great, although the inverse relationship is nevertheless quite clear. In Figure 5 the reader is given a more generalized presentation of the same information. Here, grouping into 5° classes for phi has been carried out and the mean and standard deviation calculated for each group. In addition, the principle of the moving average was used in an effort to smooth out some of the artificial inflection points caused by grouping. These two diagrams allow one to make several general conclusions.

- There is a recognizable inverse relationship between intensity of the radar echo and street orientation angle.
- There does appear to be a definite threshold value for phi of about 20° or 22°. Below this value the radar echo is quite sensitive to changes in street orientation. Conversely, greater phi values produce little change in image tone.
- Strength of the radar echo is largely predictable for street orientation angles below the phi threshold.
- The behavior of the standard deviation curve indicates that tone variations are rather small for low phi angles, but they rise to a maximum in the mid-20's (i.e., phi angle), and finally decrease to a low value as one approaches a phi of 45°. One interpretation of this latter point is that corner reflector effect is becoming more dominant at these higher phi angles, producing a consistently enhanced radar echo.

In general, these findings support and clarify the work of Waite *et al.* (1980), referred to earlier concerning row orientation of agricultural fields on Seasat imagery. Waite describes, for example, a definite lack of radar backscatter from fields with row orientations of 20 degrees or more off the perpendicular. Despite the shift in subject matter from farm land back to urban land, this effect is quite apparent here also. In Figure 5, the curve of mean image tone has a very definite inflection point at just about 20 degrees. Waite and his colleagues also describe the possible existence of a threshold at about 12 degrees. They report that fields below that value produce bright radar returns, and those in the range of 12 to 20 degrees produce medium returns. As is apparent from Figures 4 and 5, the present data indicate a more or less linear trend from 0 to 20 degrees for street orientation, with no obvious thresholds or inflections between.

If the correlation coefficients are recalculated for the subsets above and below an arbitrary phi threshold of 20°, the relationships become much clearer. As indicated in Table 2, the r-values

TABLE 2. CORRELATION COEFFICIENTS BETWEEN GREY VALUE AND PHI FOR SUBSETS ABOVE AND BELOW AN ARBITRARY PHI THRESHOLD OF 20°; COMPARE WITH FIGURE 4.

		Correlation Coefficient	
Data	No. of Test points	Below phi Threshold of 20°	Above phi Threshold of 20°
All data	231	−0.65	+0.07
Ascending orbit	91	−0.69	+0.08
Descending orbit	140	−0.64	+0.07
Baltimore	92	−0.64	−0.22
Boston	49	−0.73	+0.14
El Paso	38	−0.49	−0.06
Harrisburg	52	−0.78	−0.38

below the threshold jump to about −0.65 and those above the threshold take on fairly low values, many close to zero. The conclusion that one makes from this is that the cardinal effect operates in a linear way for street angles in the range of 0° to about 20°, but is not operating recognizably for phi angles of 20° to 45°. For those urban sites below the phi threshold of 20°, the coefficient of determination jumps from 0.23 to about 0.42. This indicates that for these sites over a third of the variation in image tone can be attributed to street orientation alone.

Figure 6 provides a pictorial illustration of the practical impact of these matters. Entire sections of the city disappear or come through strongly, depending on the street orientation of the neighborhood. It is interesting that this phenomenon is not easily recognizable as cardinal effect because it is homogeneous over the entire urban neighborhood of dozens of city blocks. Until recently the existing literature did not lead the radar image interpreter to expect this. Thus, on reconnaissance imagery of a new geographical area, for example, the interpreter could easily classify low return neighborhoods as parks or some other low intensity land use. Conversely, high-return residential areas could easily be reported as industry or some other activity involving more massive structures.

One possible solution to this might lie with digital image processing. One could, for example, create the synthetic aperture radar image of a city in such a way as to eliminate this street orientation anomaly. This would, of course, make all subsequent manual, or even digital, interpretation work from the data much simpler.

CONCLUSION

The largely random street orientation has been shown to be very important in determining the

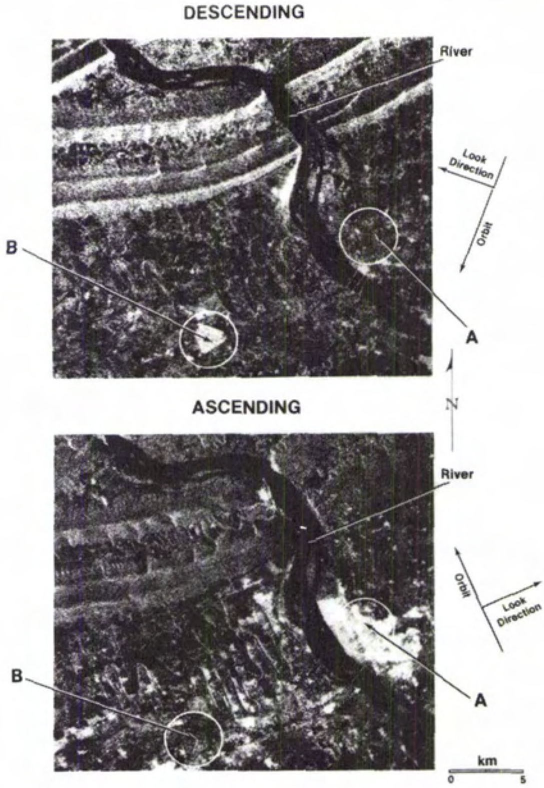

FIG. 6. Pictorial illustration of the impact of cardinal effect in urban areas on Seasat imagery. The area shown from descending (top) and ascending (bottom) orbits is Harrisburg, Pennsylvania, along the Susquehanna River. Area A is an urban area of Harrisburg and Area B is the Mechanicsburg Naval Depot. Both areas demonstrate the cardinal effect.

grey tone of urban residential areas on Seasat L-band imagery. Although cardinal effect has been recognized for many years, its effect on satellite radar data is not quite as expected. Here it strongly influences rather large sections of the city in a homogeneous and natural looking way and is thus almost insidious. These accentuated radar echoes are largely predictable for streets which are within about 20° of being perpendicular to the radar beam. At greater angles there is no apparent relationship between street orientation and average radar intensity.

The present findings serve as an important warning to would-be radar image interpreters of urban areas. Such factors as urban density, morphology, and function do not come out of the image as easily as we have expected in the past from high resolution aircraft data.

Finally, if one can say that over a third of the tone variation of the residential image is determined by street orientation alone, one is tempted to ask: What factors determine the other 60 percent? Although the radar equation attempts to supply a theoretical answer, empirical data often get to the heart of the matter better.

Acknowledgments

This work was under partial support of the Coastal Engineering and Research Center, Fort Belvoir, Virginia. In addition, the Engineer Topographic Laboratories at Fort Belvoir were most helpful regarding densitometry work. The constructive suggestions of Leonard Bryan at the Jet Propulsion Laboratory concerning the manuscript are gratefully acknowledged. Finally, thanks to Robert Schuchman of ERIM and Bruce Needham of NOAA for supplying the Sun City imagery.

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(Received 15 May 1981; revised and accepted 28 September 1981)

DENVER UPDATE

Denver Mayor William H. McNichols signs the document proclaiming the week of March 14-20 as "Surveying, Mapping, Photogrammetry and Remote Sensing Week," to honor the American Congress on Surveying and Mapping and the American Society of Photogrammetry, which will meet in Denver in 1982 for their annual joint convention. Looking on are (from left) W. A. Radlinski, executive manager of the Council of Mapping, Photogrammetry and Surveying Societies (COMPASS), James Plasker, director of the 1982 ACSM-ASP convention, and Al Letey, technical advisor for this year's convention.